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SOME STUDIES OF THE FLUCTUATIONS IN EMISSION FROM THE EXHAUST GASES OF SMALL ROCKET ENGINES

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I. INTRODUCTION

An experimental analysis has been made of the frequency spectrum of fluctuations in radiant emission from the exhaust gases of small rocket motors near the nozzle exit. The purpose of this study was to determine, if possible, an optimum chopping frequency for a device which is being designed to measure very small optical absorption (approximately 1%) in rocket flames. The principle of operation of this device has been suggested by Oldenberg.[1] In brief, the apparatus consists of a collimated beam of greybody radiation, chopped by a silvered sector disk in such a manner as to produce two sinusoidally modulated beams, 180° out of phase. One beam passes through the flame under study, and the other is used as a reference. Emission from the flame is eliminated by a synchronous amplifier tuned to the chopping frequency.

The effectiveness of this method of eliminating the radiation from the flame is restricted by the presence of a-c components in the flame emission which can be expected to exhibit roughly a $1/f$ amplitude dependency. Occasional peaks associated with resonant frequencies in the system have been observed.[2,3] The results of previous studies have indicated that the amplitude of these fluctuations also varies with propellant mixture ratio and with wavelength for laboratory-scale engines.[4] There have been some studies published in the classified literature on this subject.[5,6] The present study has been designed to determine experimentally the noise spectra for the several laboratory rocket motors which will be employed in our absorption measurements. The results will be used to select a chopping frequency for the absorption measurements.

In the absence of any other considerations, a very high chopping rate would be selected because the emission is expected to exhibit a 1/f amplitude dependence. However, the useable chopping frequency range is restricted by a number of considerations. Several rocket engines with different chamber dimensions will be employed. Resonant frequencies may be encountered in the 10- to 20-kc range under certain conditions.* At higher frequencies, limitations are imposed by the time response of such detectors as PbS. The work described in this report was restricted to frequencies in the 0- to 10-kc range.

II. EXPERIMENTAL APPARATUS

A block diagram of the experimental apparatus appears in Figure 1. The rocket engines ranged in thrust from 10 to 160 lb. Various filter-detector combinations were employed, covering the wavelength region from 0.4 to 8 μ. A 931A photomultiplier tube was employed for visible radiation, lead sulfide and cooled gold-doped germanium for the infrared. Detector outputs were amplified and recorded on magnetic tape.

Calibration of the detector-amplifier systems for frequency response was made with a tungsten strip lamp, chopped sinusoidally at 24 kc. The chopper motor was turned off, and amplitude versus frequency was recorded as the chopper wheel decelerated. The frequency response of the photo-multiplier system, as well as that of the germanium detector was flat (less than 1 db down at 10 kc). The lead sulfide data required correction prior to Fourier wave analysis, since the 10-kc frequency response was down about 6 db.

The detectors were located radially in a plane immediately adjacent to the nozzle exit, with fields of view of approximately 1 cm^2 (Exit diameters of the rocket engines varied from 0.9 to 3.7 cm.)

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*Inherent in this statement is the assumption that there is a correlation between the fluctuations in the chamber pressure and emission at the nozzle exit. A number of investigators[2] have demonstrated that this correlation does exist between the chamber pressure and chamber emission fluctuations. The estimate of resonant frequencies which may be generated is based on simple "organ-pipe" calculations.

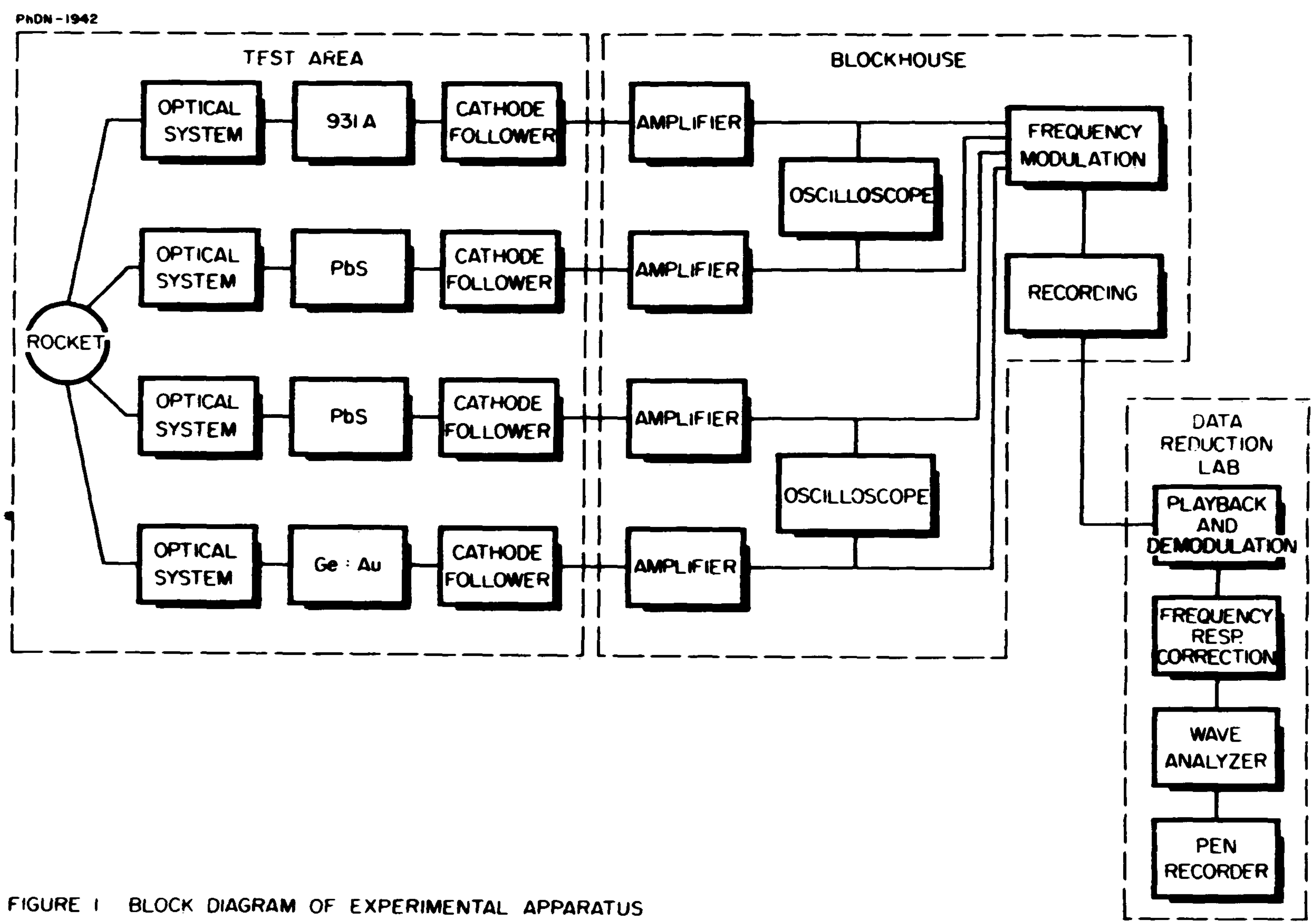

FIGURE 1 BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS

The optical paths were purged with nitrogen when tests were made in the H_2O and CO_2 emission band wavelength regions.

Because of the high acoustic noise level in the test area, all of the electronics except a simple cathode follower for each detector were located inside a blockhouse. The cathode followers utilized a 6021 triode, which has been found to be quite free of microphonics. The noise level due to microphonics in the system was obtained by firing the rocket engines with the detectors in position, but masked off to prevent any signal from flame emission. A plot of amplitude versus frequency for a typical noise check is shown in Figure 2A. Figure 2B is a similar plot of a wow and flutter check of the playback-wave analyzer system. The same amplitude scale is used in both figures. From these two figures, it is apparent that the limiting noise was due to wow and flutter, and that microphonic effects were neglible.

III. EXPERIMENTAL PROCEDURE

The rocket engines were mounted horizontally on stands outside the blockhouse. The nozzles were contoured to provide nearly axial flow at the nozzle exit and an exit pressure balanced with the ambient (sea level) pressure. Typical run durations were from three to five minutes, during which time the fuel flow rates, chamber pressure and fuel mixture ratio were determined, and the amplifier gains were adjusted to provide appropriate recorder input levels. Oscilloscopes were used for monitoring the recorder input levels. To permit d-c recording, information was frequency modulated, by using standard 70-kc modules, and then recorded on magnetic tape. One-second samples were re-recorded on tape loops, from which a plot of amplitude versus frequency was made, using a wave analyzer with a bandwidth of 200 cps. The adequacy of the sampling time was verified by comparing the amplitude versus frequency plots for data taken at three different, but consecutive, 1-sec time intervals. The results, appearing in Figure 3, indicate that the sampling time was sufficient.

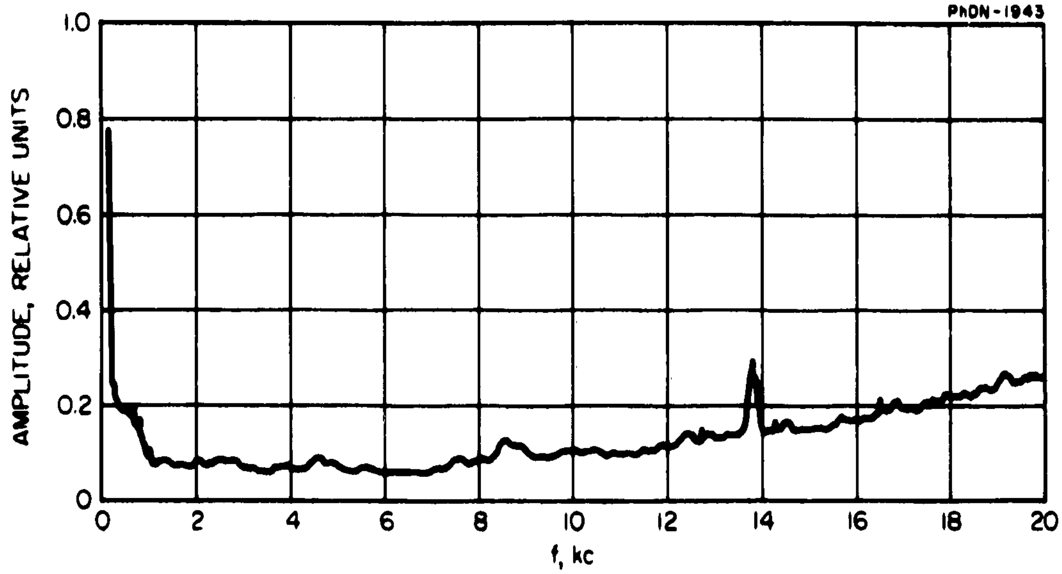

FIGURE 2a AMPLITUDE VS FREQUENCY PLOT OF SYSTEM NOISE

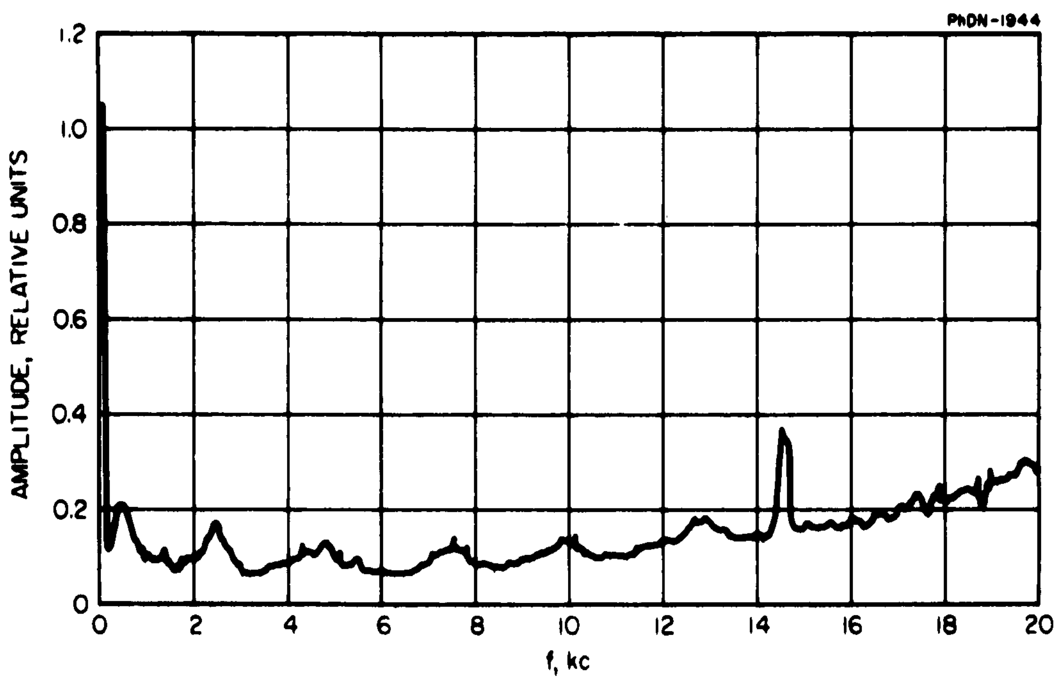

FIGURE 2b AMPLITUDE VS FREQUENCY PLOT OF WOW AND FLUTTER
AMPLITUDE SCALE IS THE SAME FOR BOTH FIGURES

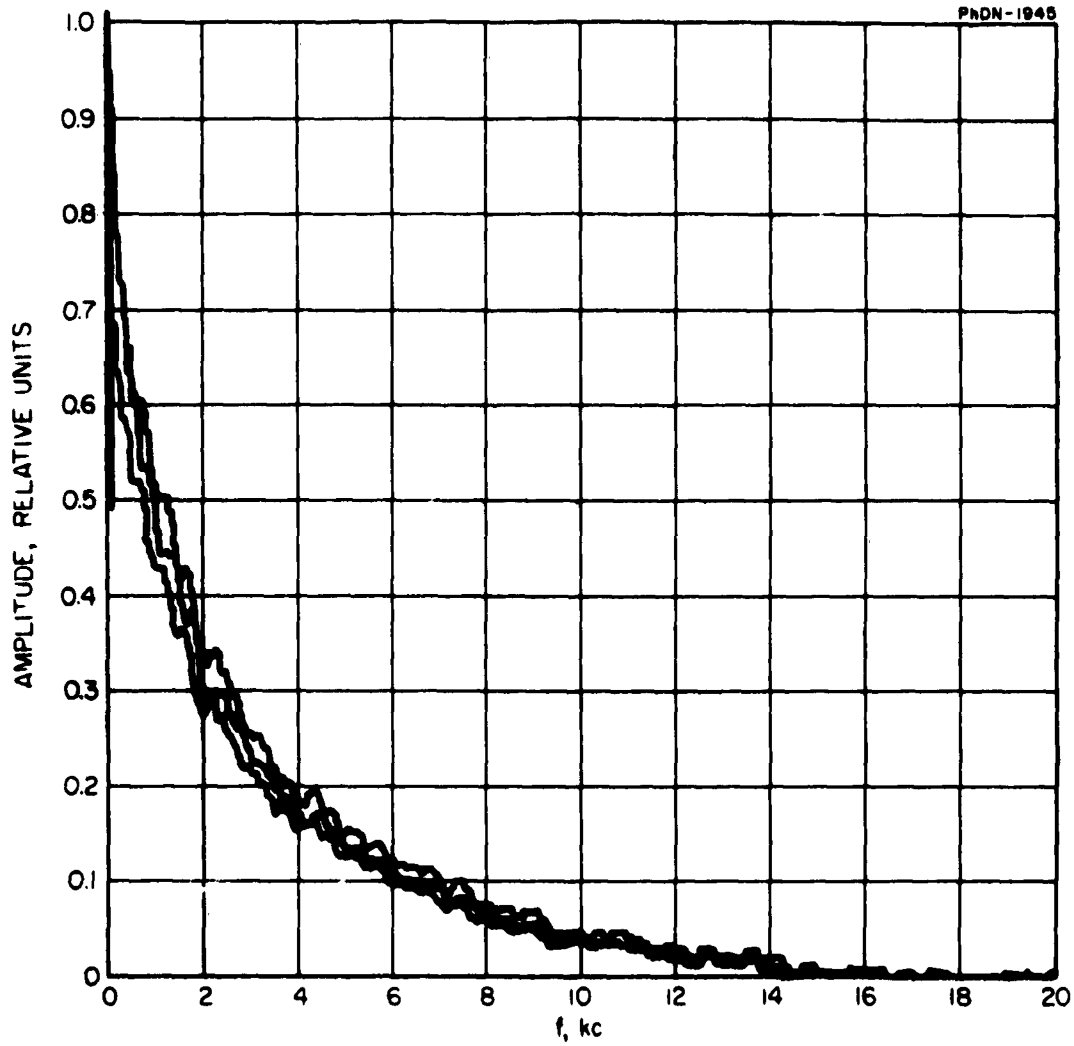

FIGURE 3 AMPLITUDE VS FREQUENCY PLOT OF THREE CONSECUTIVE ONE-SECOND DATA SAMPLES

A measure of the amplitude of the fluctuations relative to the average d-c level of emission was obtained. The d-c readout was accomplished by means of oscillograph recordings of a reduced speed playback. These data were taken just prior to engine shutdown (to provide the signal level) to just after shutdown (to provide a zero level).

IV. RESULTS

The characteristic features of the fluctuations in emission were about as expected. The total a-c component relative to average d-c level was greatest in the visible region, with typical a-c to average d-c ratios as high as 100% for fuel-rich operating conditions. This high value is probably attributable to the presence of small carbon particles in the flame. At longer wavelengths, and in particular, in the 2.7μ water vapor region and 4.3μ carbon dioxide region, the molecular emission exceeds that of the carbon, and the a-c to average d-c ratios are typically less than 50% (Figure 4). As the mixture ratio approaches stoichiometric, the a-c to average d-c values approach a minimum (5 to 10% at the longer wavelengths) and then show an increase for fuel-lean operation.

Figures 5 through 9 illustrate the frequency dependence of the a-c component of the flame emission. In these figures, the raw data have been corrected for system frequency response and approximately for noise caused by wow and flutter in the playback system, then smoothed and normalized arbitrarily at 2 kc to facilitate comparison. Figure 5 is a composite of photomultiplier data from a series of tests using the 160-lb thrust engine. Figures 6 and 7 are similar presentations of lead sulfide and gold-doped germanium data. In Figure 4, it appears that the frequency spectrum is more reproducible at either fuel-lean or fuel-rich mixtures than at near-stoichiometric conditions. This may be attributable, at least in part, to the fact that at near-stoichiometric conditions the relative amplitude of fluctuations is at a minimum, and the resultant decrease in signal-to-noise is accompanied by a greater uncertainty in the data.

Figure 8 illustrates a comparison of photomultiplier data from the three engines operating fuel-rich, and Figure 9 shows a similar comparison of lead sulfide data.

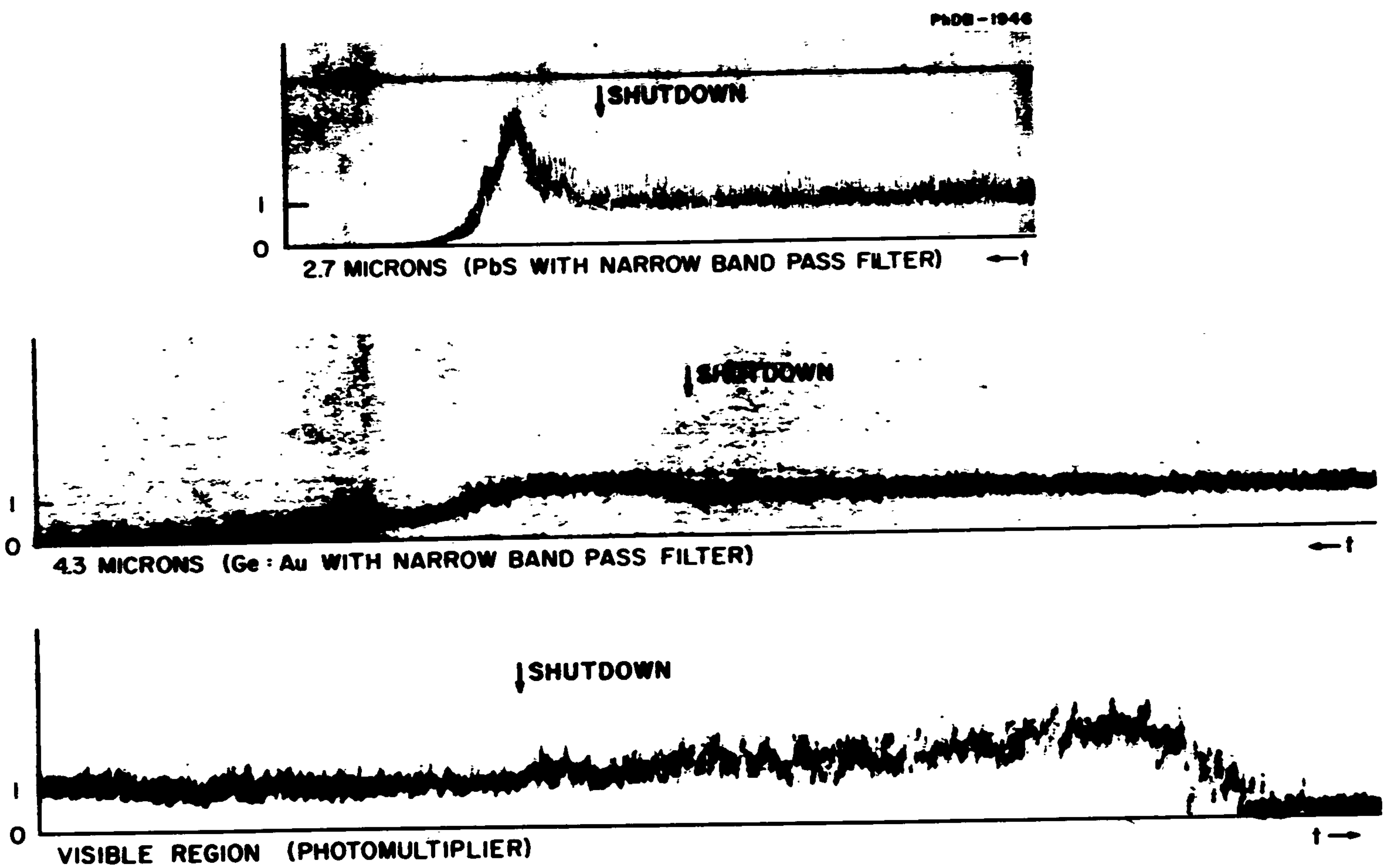

FIGURE 4 COMPARISON OF AC TO DC AMPLITUDES IN THREE DIFFERENT WAVELENGTH REGIONS
(NOTE CHANGE IN DIRECTION OF TIME SCALE IN THE THIRD REPRODUCTION)

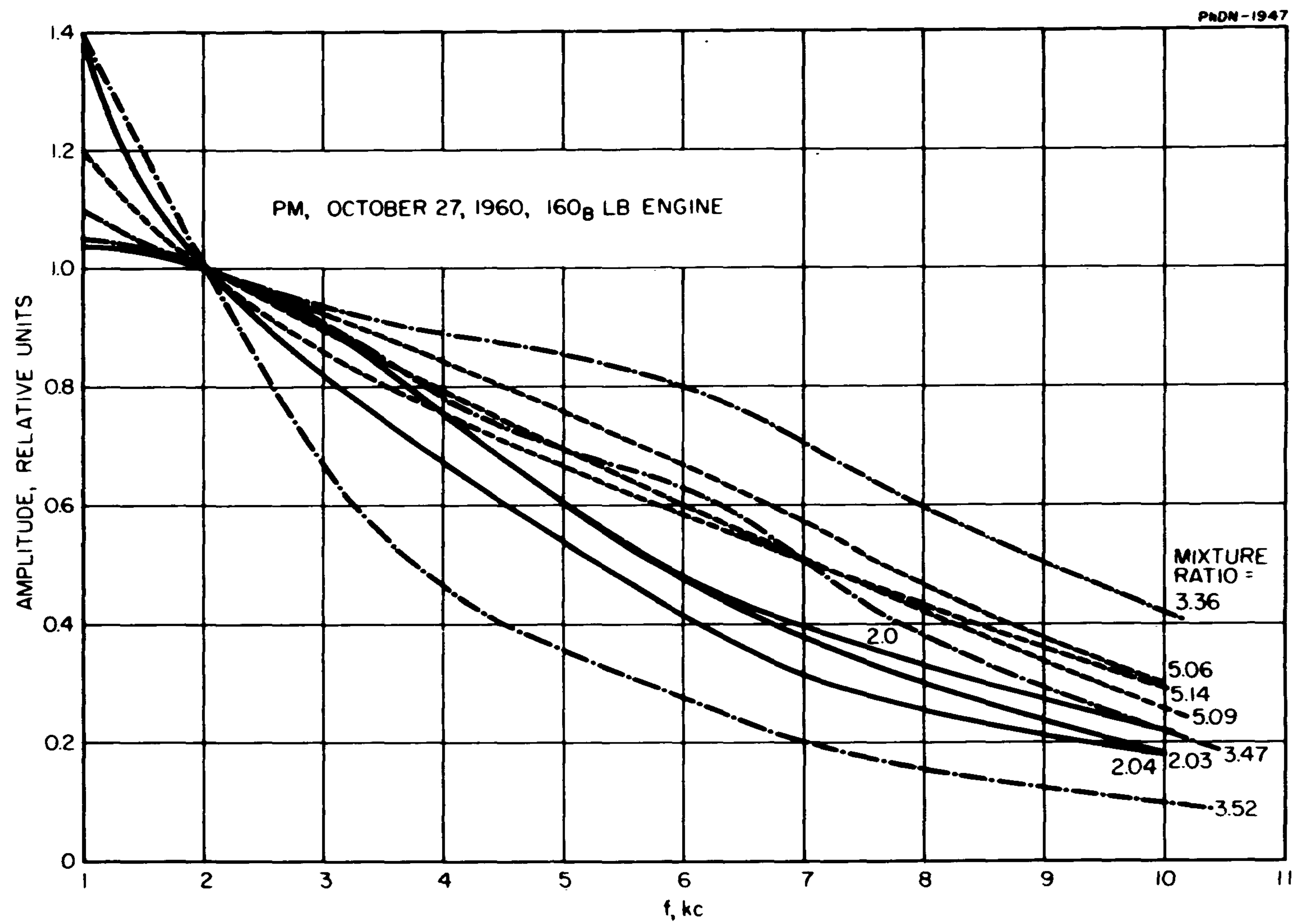

FIGURE 5 AMPLITUDE VS FREQUENCY IN THE PHOTOMULTIPLIER WAVELENGTH REGION FOR 160-POUND THRUST ENGINE AT VARIOUS MIXTURE RATIOS

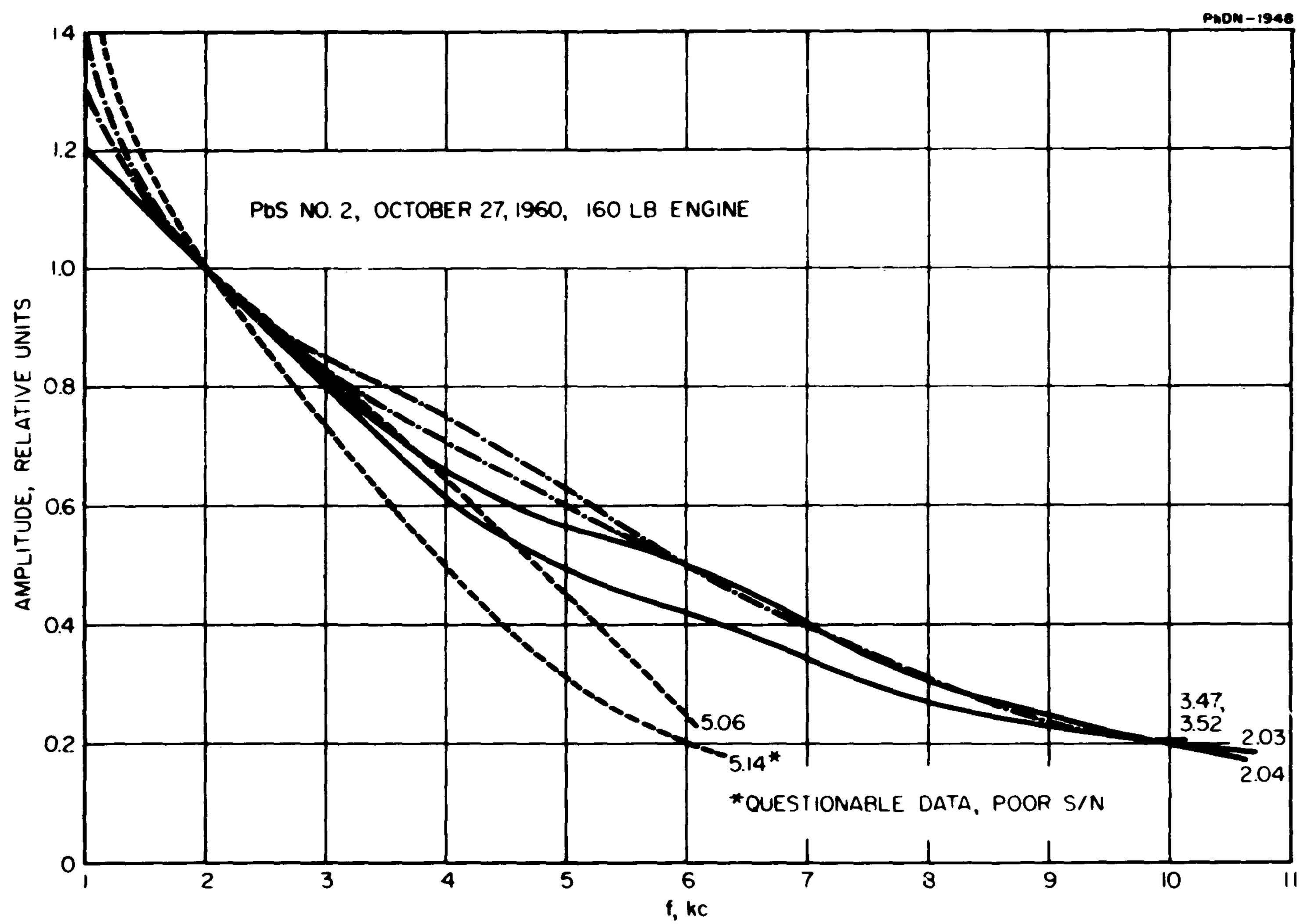

FIGURE 6 AMPLITUDE VS FREQUENCY IN THE LEAD SULFIDE WAVELENGTH REGION FOR 160-POUND THRUST ENGINE AT VARIOUS MIXTURE RATIOS

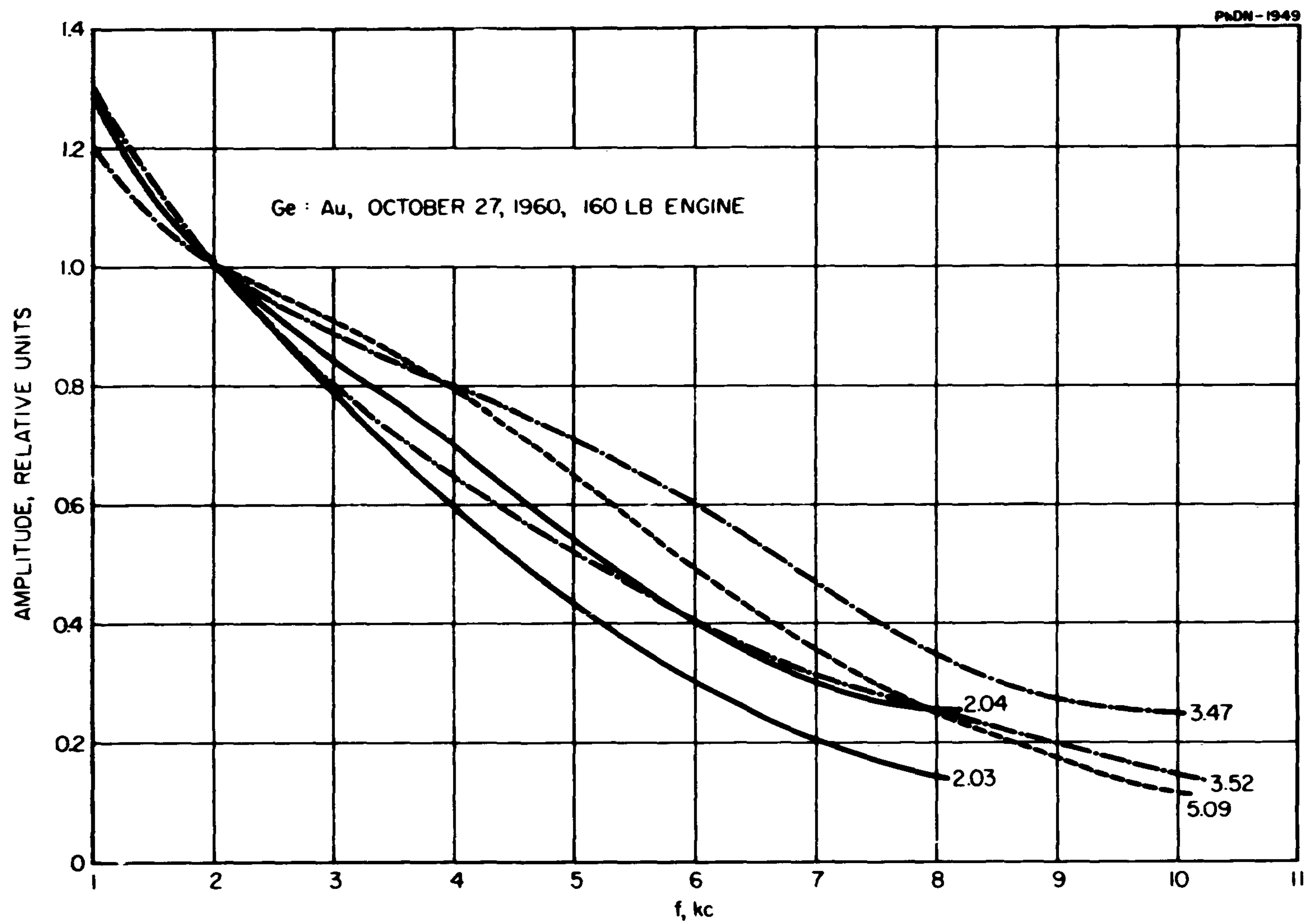

FIGURE 7 AMPLITUDE VS FREQUENCY IN THE GOLD-DOPED GERMANIUM WAVELENGTH REGION FOR 160-POUND THRUST ENGINE AT VARIOUS MIXTURE RATIOS

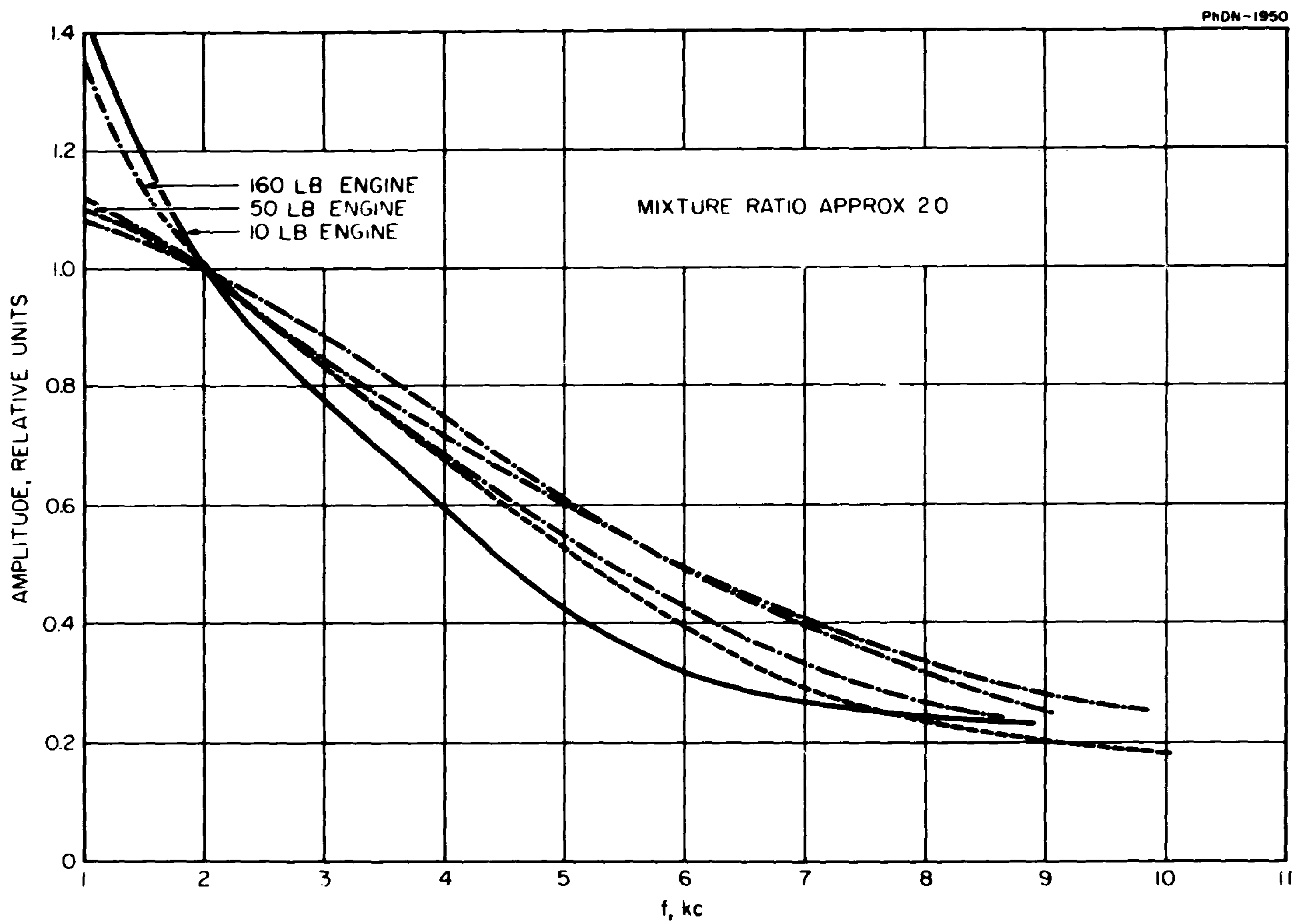

FIGURE 8 COMPARISON OF PHOTOMULTIPLIER DATA FOR THREE DIFFERENT ENGINES, OPERATING FUEL-RICH

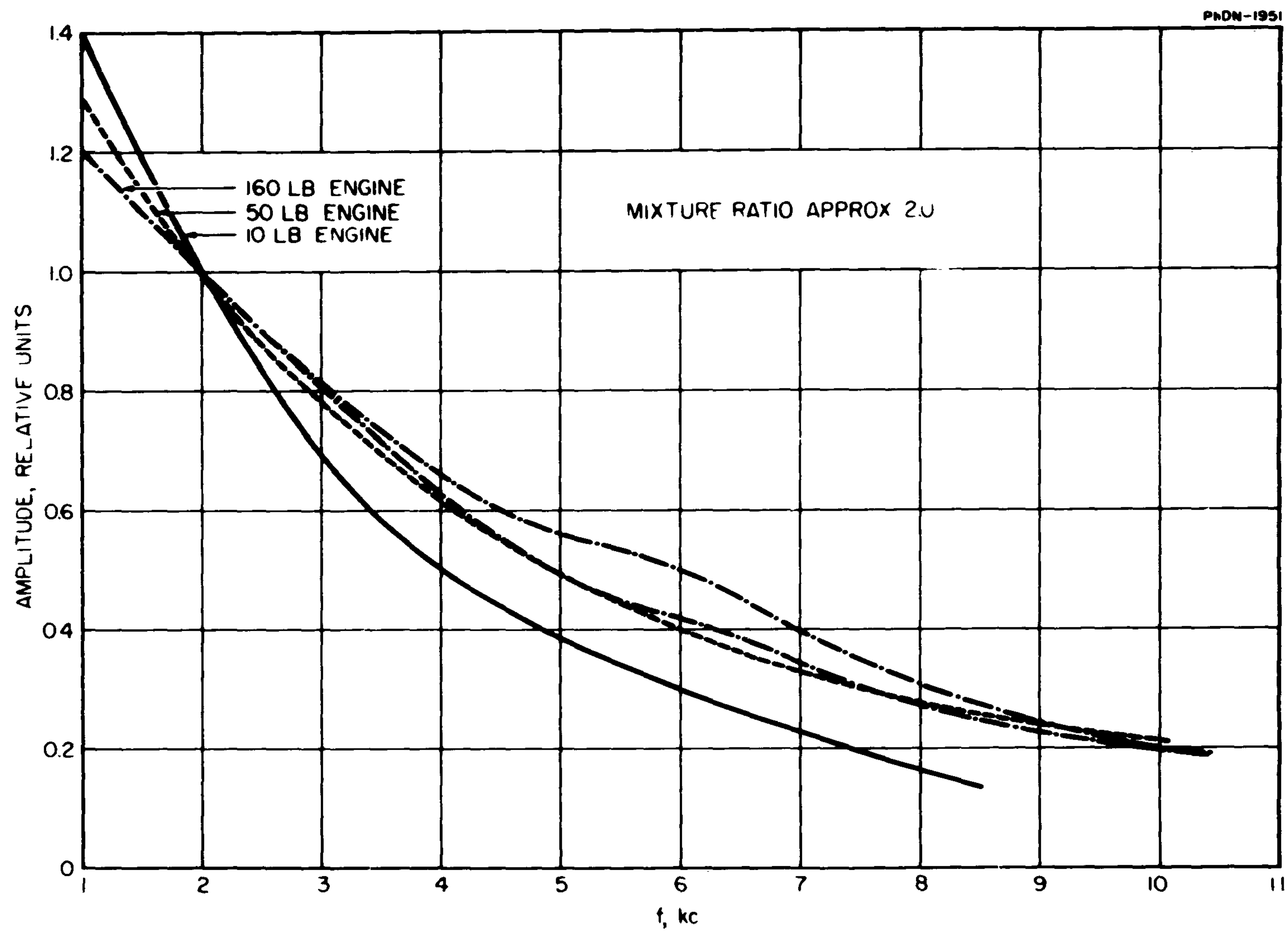

FIGURE 9 COMPARISON OF LEAD SULFIDE DATA FOR THREE DIFFERENT ENGINES, OPERATING FUEL-RICH

None of the three engines at either fuel-rich or stoichiometric mixture ratios produced significant resonant peaks in the amplitude versus frequency plots at frequencies up to 10 kc. When the engines were operated fuel-lean, however, strong oscillations at reproducible frequencies were observed. For the 160-lb engine, this frequency was about 640 cps. This frequency was probably associated with chugging (a coupling between the propellant supply system and the combustion chamber conditions), since there are no dimensions characteristic of the engine itself which could produce oscillations in this low frequency range. At a mixture ratio of approximately 5:1 a strong resonance appeared occasionally in the 160-lb engine, and at 7:1 or more its occurrence was persistent.

To determine the extent to which this disturbance was propagated downstream in the exhaust plume, two lead sulfide cells were mounted in such a fashion that one monitored the emission at the nozzle exit and the other could be positioned at various stations downstream. In Figure 10, the Fourier analysis of the fluctuations at the nozzle exit are compared with simultaneous recordings at several downstream positions (wave analyzer band width was 5 cps). The peak amplitude diminishes with increasing distance from the nozzle, and finally disappears at about a 20-diam distance. From phase difference measurements, the propagation velocity of this disturbance was found to be approximately 4500 ft/sec at the nozzle exit, decreasing almost linearly to zero ft/sec at 20-diam downstream.* The resonant frequency changed from 640 to 600 cps as the position of the detector was moved from the nozzle exit to 20-diam downstream. The bandwidth of the amplitude peak increased slightly as the detector was moved away from the nozzle exit.

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* By measuring the phase difference between the two detector outputs, the average propagation velocity of this disturbance was determined for several positions. Any two of these measurements were sufficient to determine both the instantaneous velocity and the average deceleration of the disturbance. The several values of the average deceleration thus obtained agreed to within 3%, which indicated that the deceleration was constant, and thus it was possible to calculate the instantaneous velocity at the nozzle exit by extrapolation.

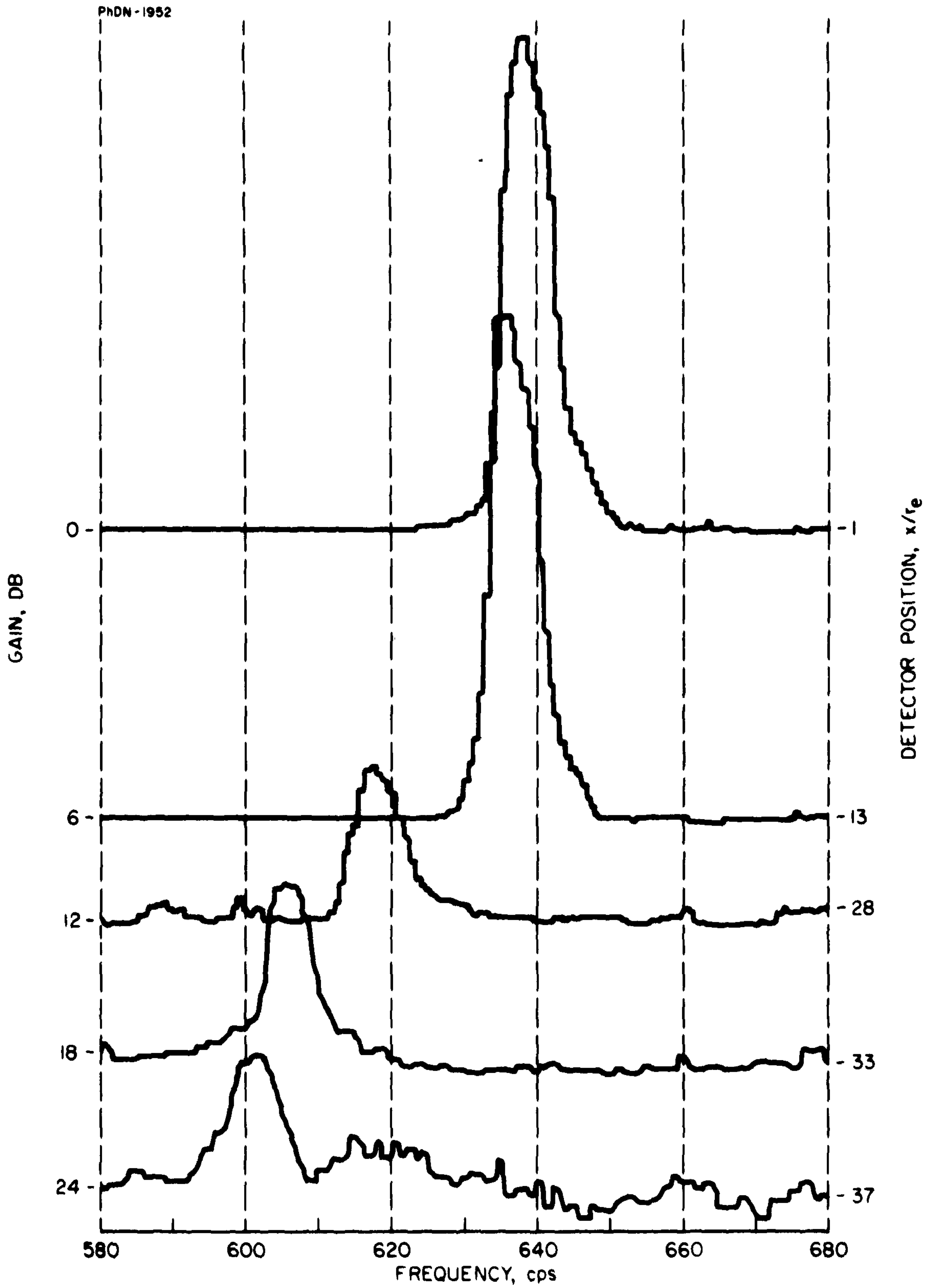

FIGURE 10 WAVE ANALYSIS OF RESONANT EMISSION FOR VARIOUS POSITIONS DOWNSTREAM OF THE NOZZLE EXIT (5cps WAVE ANALYZER BANDWIDTH)

Similar resonant peaks were observed at approximately 600 cps for fuel-lean runs of the smaller engines, but the amplitude of the resonant peak was small compared to the typical (1/f) noise at that frequency.

SUMMARY

With the exception of a narrow frequency range in the neighborhood of 600 cycles, the frequency spectra of emission fluctuations to 10 kc for the small engines studied appear to be quite similar. In view of the (roughly) 1/f nature of the amplitude distribution, the selection of an optimum chopping frequency for absorption measurements can be based upon mechanical and electronic considerations in the 1- to 10-kc range.

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